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Thomas C. Mowatt, Joseph A. Dygas,
Christopher Gibson and Aden L. Seidlitz

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Mineral Resources of Western Arctic Alaska

Abstract

The area of concern encompasses that portion of Alaska north of 68° latitude and west of 151° longitude, including the National Petroleum Reserve in Alaska (NPRA).

The southern portions of the area are underlain by Mesozoic-Paleozoic sedimentary rocks, with some associated intrusive and extrusive igneous rocks. These are, in part, similar to the rocks which host the world-class Red Dog base and precious metals (Zn, Pb, Ag) deposit, which lies in the southwestern portion of the study area. There are a number of analogous occurrences of mineralization known within the southern part of the study area (e.g., Drenchwater Creek, Kivliktort Mountain, Story Creek), as well as other showings and geochemical anomalies perhaps related to similar mineralization. Other potential metallic-nonmetallic mineral resources within the study area include platinum-group elements, chromium, copper, uranium, metalliferous "oil shale," fluorite, and bentonite.

The study area contains known mineral resources, but remains to be investigated at the level required to elucidate potential and significance.

1. Introduction

The study area, which includes all of the National Petroleum Reserve in Alaska (NPRA), as well as contiguous portions of Alaska to the south and west, is shown on *Figure 1*. For present purposes, the area has been defined as that portion of Alaska north of latitude 68°, and west of longitude 151°. The discussion herein will address only metallic and nonmetallic mineral resources, and will not deal with coal, petroleum, etc., in any detail.

Information has been drawn from a number of sources, published as well as unpublished. Principal summary sources were the "National Petroleum Reserve–Alaska (105(c) Land Use Study" (U.S. Department of the Interior, 1978), "Mineral Terranes of Alaska, 1982" (U.S. Bureau of Mines, and C. C. Hawley, 1982), and the mineral resources portions of a U.S. Bureau of Land Management Resource Management Plan for the "Western Arctic" (Mowatt, 1990, in draft form). The U.S. Department of the Interior carried out a multi-disciplinary land use and resources study ("105C study") of the NPRA, 1976-1978, and the

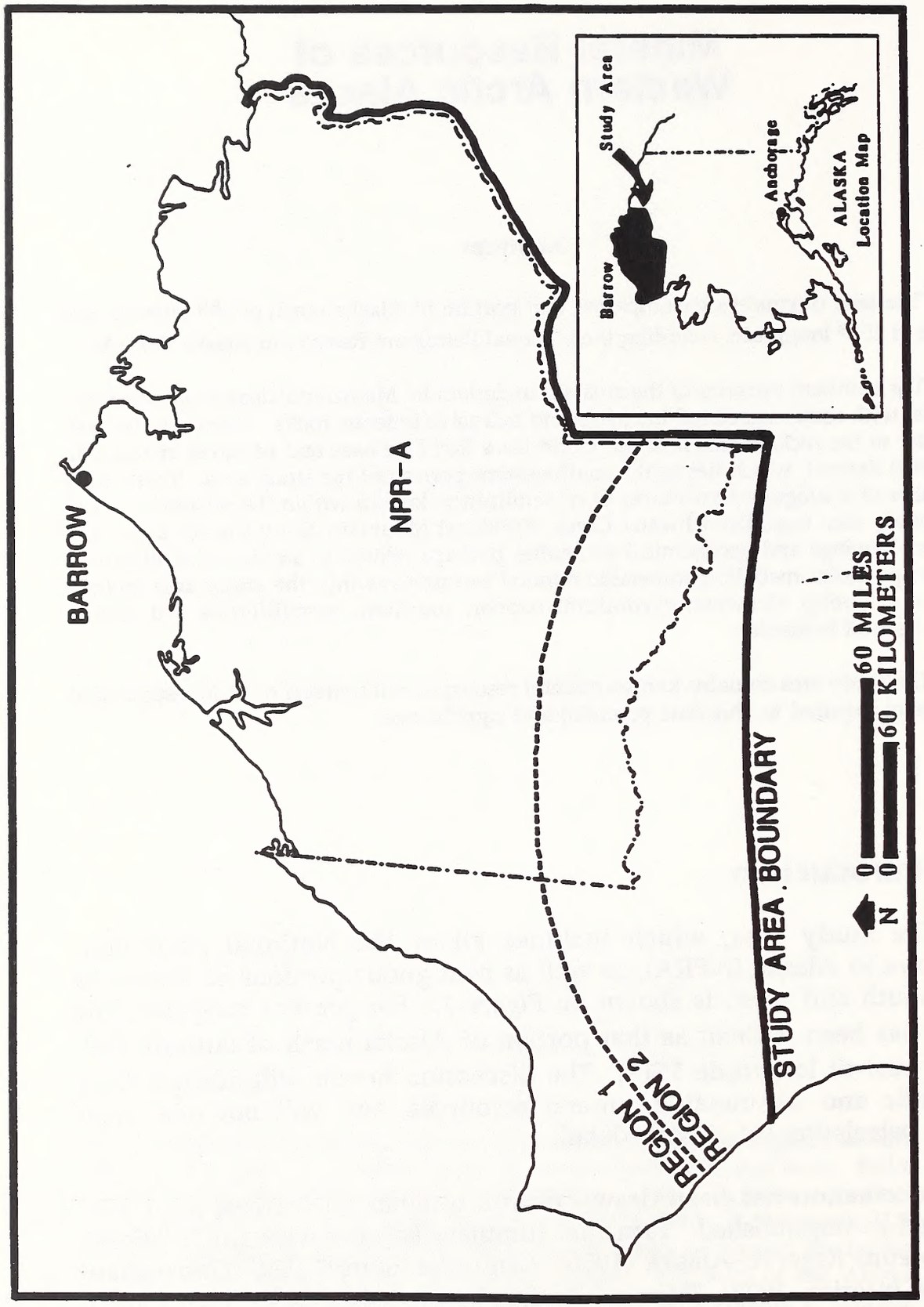

Figure 1. Location of the study area.

results were published in 1978 (U.S. DOI, 1978). Much of the following discussion is drawn directly or indirectly from this work, with which the senior author had substantial technical involvement.

To date, there has been no known production of metallic-nonmetallic mineral resources from within the boundaries of NPRA, nor is significant production known to have taken place elsewhere within the study area. However, in the southwestern portion of the area, in the Wulik River region, the world-class Red Dog base - and precious metal (zinc, lead, silver, principally) deposit began production during 1990, perhaps to eventually become the largest mine of its kind in the western world (cf. Moore et al., 1986; Giegerich, 1986; Mowatt et al., 1990).

Mineralization quite similar in aspect to that at Red Dog has been recognized in analogous geologic settings in a number of places elsewhere in northwestern Alaska. The geologic terrane which hosts the Red Dog deposit trends north and east from the Wulik River area, across adjacent portions of the Noatak National Preserve (established subsequent to the 1975 recognition of the Red Dog deposit), and the southern portion of the National Petroleum Reserve in Alaska (NPRA), continuing on far to the east in a somewhat ill-defined regional belt.

A number of base and precious metals (principally zinc, lead, silver) mineral occurrences, as well as extensive geochemical anomalies (zinc, lead, arsenic, barium, silver, chromium) were recognized by the reconnaissance studies by the USBM and USGS during 1977-1978 (Jansons, 1982). Five distinct geochemical and geological associations have been identified within this belt. To date, at least four zones of significant base metal mineralization have been elucidated: (1) Drenchwater Creek; (2) Kivliktort Mountain; (3) Story Creek; (4) Whoopee Creek.

Particularly interesting is the occurrence at Drenchwater Creek, some 100miles to the east of Red Dog. The Drenchwater Creek locality has been studied and reported on by federal agencies (USGS, USBM) in similar fashion to the preliminary work for Red Dog.

There is a major difference, however, in that Drenchwater Creek and environs, as well as most of the other occurrences/anomalies, lie within the NPRA, which has been closed to private sector mineral claim-staking for many years. Thus, the subsequent follow-up work required to determine the presence or absence of viable mineral deposits has not been done.

Given the present land status and federal policy, development is precluded, hence potentially significant mineral resources remain recognized, but unevaluated. Additionally, large areas of land between the Red Dog area and the Drenchwater Creek/southern NPRA area, as well as to the south, have been removed from mineral resource exploration-development by incorporation into the Noatak National Preserve and Gates of the Arctic National Park.

There are many similarities in geologic relationships across the region, but sufficient work to substantively assess mineral resource potential was not done prior to the designation of the Noatak National Preserve and Gates of the Arctic National Park, though the Red Dog deposit had been recognized at that time. No work of this nature has been done since, of course. This situation needs to be addressed in terms of the socio-economic context in order for any further technical work to proceed.

2. General Considerations

During the course of a variety of types of investigations of northern Alaska over many years, general knowledge of the geologic characteristics and relationships of the region has been developed. Much of the earliest work appropriately emphasized geologic mapping, on relatively small scales. Somewhat more detailed work followed, principally focussed on oil and gas resources, as well as coal.

Prior to 1975 (recognition of Red Dog deposit), however, little specific attention had been paid to metallic-nonmetallic mineral resources per se. In the context of the 105(c) study carried out by the federal government, in 1977-1978, a joint program between the U.S. Bureau of Mines (BOM) and the U.S. Geological Survey (USGS) specifically initiated mineral resource field-investigation programs in the southern part of the NPRA, primarily restricted to the Mesozoic and older rocks south of the Colville River between west longitudes 156 and 162.

Geologic field data were also collected in areas adjacent to the NPRA where such information was deemed to be pertinent to a mineral resource evaluation of NPRA proper. Under this program, field mapping and regional geochemical studies were done by the USGS, and known or suspected mineralized areas were investigated by the BOM. Additional data compilation and synthesis emphasizing resource potential were also done by both agencies.

Recommendations for further mineral resource work were developed on the basis of: evaluation of known resource-related information; identification of areas that need further field studies; and identification of the types of work that would yield the most useful data. No additional systematic work was done subsequently, until 1991, at which time collaborative efforts by United States Department of the Interior agencies (USGS, BOM, Bureau of Land Management-BLM) were resumed, on a reconnaisance scale.

At this time, it is possible to present only broad generalizations regarding geologic relationships between mineral occurrences, rock types, and geologic environments and, from these, broadly characterize mineral resource potentials that are likely to exist in the Western Arctic study area. In most instances, it is possible only to delineate potentially mineralized regional trends. More specific designation of areas of interest regarding mineral resources will be possible only after considerably more field and ancillary laboratory work.

At present, relatively few specific sites have been investigated, and these only in a relatively superficial manner. Of these, none have been studied with sufficient thoroughness to permit a rigorous mineral appraisal which would allow an evaluation of reserves. The following analysis of the mineral resource situation is based on the available (minimal) geologic data. Additional data, and careful interpretation of such data, are necessary for a realistic comprehensive assessment of the mineral resources.

3. Mineral Resources

Discussion of mineral occurrences of potential significance is necessarily generalized because of the low level of geologic knowledge of the study area. Known and speculative resources include metallic and nonmetallic deposits, and radioactive minerals; reserve estimates of these commodities cannot yet be made.

Occurrences of metallic and nonmetallic minerals have been reported from several areas across northern Alaska (Tailleur and others, 1970, 1976; U.S. Geological Survey Open-File Reports 78-70A-D, 1978; 1977-1978 data on file with USGS and BOM; Jansons and Mowatt, 1978; U.S. Bureau of Mines MLA 121-82, OFR 103-78, 65-78, 38-80, 26-81; U.S. Department of Interior 105(c) Study, 1978; Einaudi and Hitzman, 1976; Lange et al., 1985; Moore et al., 1986; Forrest and Sawkins, 1987; Mowatt et al., 1990.

The minerals potential of the study area may be described in terms of two regional geologic settings (*Figure 1*), a southern region (2) of relatively older (mid-Paleozoic through mid-Cretaceous) rocks, and a northern region (1) of younger (Cretaceous and younger) rocks. Each of these settings possesses geologic characteristics which may be related to known mineral occurrences. These characteristics may be used to infer the possible existence of potential, but as yet undiscovered, mineral resources as well.

The southern region contains, or is adjacent to, known occurrences of phosphate rock, metalliferous oil shale, zinc, lead, silver, barite, chromite, platinum group elements, copper, and fluorite. Additional similar occurrences, as well as other mineral commodities which are commonly associated with the geologic environments known to be present in the region, can be expected to be found.

The northern region contains not only significant known coal deposits, but also considerably greater amounts of coal whose extent, thickness, and character remain to be determined. Additionally, the geologic setting in this region is permissive for the presence of a variety of mineral resources including uranium, base and precious metals, and nonmetallic materials. Analyses of previously sampled materials from this region, and geochemical anomalies, support the potential existence of these other commodities.

In addition to the Red Dog mine, the only mineral production at the present time (excluding natural gas near Barrow) is the limited and variable extraction of coal, sand, and gravel for local use by inhabitants of villages within and immediately surrounding the study area. Mineral entry under the Mining Law of 1872 has been prohibited in NPRA since the establishment of the Naval Petroleum - Reserve Number Four in 1923.

However, along the regional geologic trend of Region 2, to the west and south of NPRA, base and precious metal mineral deposits of substantial size and grade (Red Dog, Lik) have been discovered; Red Dog was brought into production in 1990. Einaudi and Hitzman (1986) summarized the mineralization and known regional geology as follows:

> In northwest Alaska, a belt of dominantly shale-hosted (Zn-Pb-Ba) deposits occurs within thrust sheets of Mississippian shale, sandstone, and limestone and extends from the Lik-Red Dog area eastward for nearly 250 km to the Drenchwater Creek and Story Creek prospects (*Figure 2*). The Lik, Red Dog and Drenchwater Creek

> deposits are shale-hosted, stratiform sulfide-(barite) bodies. Lik dominantly is composed of well-laminated sulfides rich in pyrite (Forrest, 1983), whereas the Red Dog and Drenchwater Creek deposits consist of lenses of poorly laminated massive to disseminated sulfides and barite... A number of other stratiform Zn-Pb deposits recently have been discovered in the immediate Lik-Red Dog area... but have not been described. Stratiform barite without associated sulfides is found within what is believed to be the same sedimentary succession at the Nimiuktuk prospect 100 km east of Red Dog (Mayfield et al., 1979). The northwest Alaska Zn-Pb-Ba belt also contains a number of poorly known occurrences of disseminated, vein-controlled, and breccia-hosted sphalerite and galena within Upper Devonian to Lower Mississippian sandstone, siltstone, shale, and limestone, such as Ginny Creek (Mayfield et al., 1979) and Story Creek (Ellersieck et al., 1982).

Jansons (1982), who was instrumental in their recognition, discusses base and precious metal occurrences within the region.

Field work during 1977 and 1978 in the southern portion of NPRA resulted in the discovery and recognition of significant amounts of high-grade mineralized rock (stratiform zinc and lead sulfide deposits, with silver and cadmium) at three localities, and lesser amounts of the same minerals at other localities. These mineral localities are spatially closely related to two of several regional geochemical and geological trends recognized to date in the southern part of NPRA (Theobald and Barton, 1978, 1988): chert-shale-volcanic rocks, with or without carbonate rocks, of Mississippian through Triassic ages that underlie the western zone, and (2) shales and sandstones of Devonian age that underlie the eastern zone. *Table 1* illustrates some of the results of this work.

These zones are part of a geologic belt which extends eastward from the zinc-lead-silver and barite deposits in the western DeLong Mountains outside the NPRA (Red Dog Creek, Wulik River areas) and across the southern portion of NPRA. This belt includes the impressive showings found in the Drenchwater Creek-Wager Creek area.

Extensive high-grade zinc-lead-silver deposits have been located at this site. Analytical results show the presence of up to 26 percent zinc, 5.9 percent lead, and 5.84 ounces per ton silver. The immediate geologic exploration target zone in this area is at least 7,000feet (ft) to

possibly 10,000 ft long; the associated regional geochemical target zone suggests that it may be even larger than this, and range to at least 20 miles (mi) in an east-west direction and four miles in a north-south direction.

Three specific mineralized horizons and three different types of base metal sulfide mineral-rock associations are present within this target zone at the Drenchwater area. The stratigraphically lowest mineralized unit is a black shale in which a two-ft- (0.6-m-) thick sphalerite bed, or lens, containing about 23 percent zinc has been found. These black shales also contain geochemically anomalously high lead values.

The second zone of mineralization contains "massive" sulfides and appears to be at or near the top of a thin, south-dipping acid (felsic) volcanic sequence which is several hundred feet higher stratigraphically than the mineralized black shales. The highest grade assay of the massive sulfides to date shows the presence of 31percent zinc and 8.4 percent lead.

The third zone is a dark gray chert bed at Drenchwater Creek which contains up to 11.0 percent zinc and 5.1 percent lead. These mineralized cherts apparently overlie the shales and underlie the felsic volcanic rocks mentioned above. Deposits of these types appear to have formed contemporaneously with volcanic activity (perhaps of rather quiescent type) associated with a marine depositional environment, as indicated by the chert-shale-volcanic rock association with the mineral occurrences.

The entire part of NPRA and adjacent areas (Region 2, *Figure 1*) in which this chert-shale-volcanic rock assemblage occurs must be considered as favorable for other similar deposits. Of prime interest for surface and near-surface mineralization are the areas where geochemical anomalies suggest an increase in the elements of interest. Available data permit only qualitative evaluations of resource potential. More effort certainly appears to be warranted to define resource potential within this belt.

As eastern regional geochemical trend with associated mineralization has been identified along the southern boundary of the NPRA from Story Creek east to at least Koiyaktot Mountain (table 1). Analyses of some materials, but not the most highly mineralized, from Story Creek indicate 18.5percent lead and 19 percent zinc. Materials from the Kivliktort Mountain site (*Table 1*) within this trend have not been analyzed completely, but are similar, and may contain similarly high values.

The 1977-1978 field work by the BOM resulted in the recognition of some forty-one noteworthy localities, termed "locations and surface materials of possible exploration targets" (DOI, 1978, p. 8-10). These are summarized in table 1 (from DOI, 1978).

In the DeLong Mountains quadrangle (Red Dog, Wulik River) area, potentially economically valuable concentrations of barite are found associated with the zinc-lead-silver deposits. Similar barite occurrences have not yet been noted within NPRA, although geochemically high barite values are associated with geochemically anomalously high zinc and lead values in NPRA. This suggests the possibility of finding barite deposits within NPRA as well, since this relationship is commonly found in many other mineral deposits worldwide.

Fluorite occurrences at Mount Bupto (*Table 1*) remain to be more thoroughly investigated. Fluorite is not uncommonly found in close association with zinc, lead, and barium in chert-shale-carbonate rock sequences in mineral deposits elsewhere in the world. Such rocks are present at Mount Bupto.

Immediately adjacent to the southern border of NPRA, the mafic and ultramafic igneous rock types found in the Siniktanneyak Mountain area are commonly associated elsewhere worldwide with significant deposits of chromium, nickel, platinum-group elements, and copper; often, as well, with asbestos, talc and jade. Geophysical, geochemical, and geological data suggest possible extension, or derivative deposits (placers?), of these rocks onto NPRA along the southern border. The potential for resources of this type should be investigated further.

At Siniktanneyak, as well as to the west and south, in similar geologic environments featuring mafic-ultramafic igneous rocks, there are known occurrences of platinum, palladium, copper and chromite. As summarized recently (Mowatt and Mowatt, 1990):

> Extensive bodies of mafic-ultramafic igneous rocks outcrop in northwestern Alaska, in the Noatak River region. Principal occurrences are at Rabbit Creek, Avan River, Misheguk Mountain, Agashashok River, and Siniktanneyak Mountain. Investigations of these localities, as well as peripheral surficial materials, demonstrate relatively high concentrations of platinum (Pt; 412-1826 ppb) and palladium (Pd; 343-1426 ppb), associated with zones of sulphide minerals.

Discrete platinum-metal mineral phases have been recognized,

microscopically, associated with chromite in ultramafic rocks from these localities as well (Mowatt, unpublished data). Most of these localities are now in areas presently withdrawn from mineral entry, hence remain unevaluated as to resource values.

Regional geochemical reconnaissance work in 1977 revealed several large zones of anomalously high concentrations of a variety of elements within southern NPRA and environs. Theobald and Barton (1978) depict and discuss the distributions of geochemically anomalous values for zinc, lead and barium. The geochemical data indicate three major zones which are characterized by different underlying rock types.

In Zone 1, high lead, arsenic and other values are related to Cretaceous sedimentary rocks. In Zone 2, anomalously high zinc and barium values are related to Mississippian sedimentary rocks of the Kagvik sequence, as defined by the USGS. The mineralization at Drenchwater Creek is within this zone. In Zone 3, anomalously high zinc and lead values are related to Devonian quartzites and shales. Prospecting by the U.S. Bureau of Mines (Jansons, 1982) in areas of these geochemical trends led to the discovery of high-grade zinc and lead mineralization in the Story Creek and Kivliktort Mountain areas.

Lesser amounts of similar mineralization were found at other sites along these trends. Based on significant mineral occurrences associated with the geochemical trends, these areas must be considered favorable for the occurrence of any or all of the types of minerals just discussed, and perhaps other types which have not been recognized to date. It should be stressed that all of this work to date has been limited to surface sampling, as a matter of policy. There is yet no subsurface control, merely geologic inferences.

Cretaceous and younger rocks representing nonmarine/ nearshore-offshore marine sedimentary depositional environments, which underlie about 60 percent of NPRA (Region 1, *Figure 1*), must also be considered potential sites for the occurrence of commodities which are often associated with these types of sedimentary assemblages. Base and precious metals, mineral fuels, radioactive minerals, and nonmetallic minerals are known to occur elsewhere in the world within this type of geologic setting. To date, with the exception of coal and bentonite, only sparse geochemical evidence suggests the existence of any of these commodities within the Cretaceous and younger rocks in the study area.

Bentonitic clays are not uncommon in the Cretaceous rocks of northern Alaska, but little has been published as to their character, extent, and thicknesses. Samples from two horizons which crop out

near Umiat have been analyzed thoroughly (Anderson and Reynolds, 1966). They are described as montmorillonites with certain beidellitic characteristics. Additional sampling and analyses are necessary to determine the potential resource significance of these and other bentonite horizons of the area.

Little is known regarding the presence of radioactive minerals in the study area. However, sparse geochemical data have indicated that there may be some enrichment of uranium in sedimentary rocks in Region 1.

Helium, a daughter product of the radioactive decay of uranium, has been reported in some drill holes in NPRA. Sedimentary rocks whose depositional environments and post-depositional histories are similar to those in NPRA host uranium deposits elsewhere.

Of particular interest are the Cretaceous and younger sedimentary sequences, with their associated sandstones, bentonitic materials, coal, and organic-rich rocks (Payne and others, 1952; Krynine, 1954; Collins and Robinson, 1967; Brosge and Tailleur, 1971). There are a number of associated volcanic ash horizons. These sequences comprise a very large, northern, portion of the study area. Rocks of Region 1 must be considered permissive for the occurrence of accumulations of uranium, but the presence of any uranium reserves is uncertain.

Additionally, uranium is also known to be directly associated with coal, oil shales, and phosphate rocks elsewhere. Radiometric anomalies have been reported associated with rocks underlying some of the coal horizons in the NPRA. The potential for other types of uranium deposits (veins, etc.) to exist within the study area cannot yet be assessed, but cannot be completely discounted.

Eakins (in Eakins and Forbes, 1975, p. 267-275) summarizes several aspects of the potential for occurrences of uranium resources in northern Alaska. Some preliminary work also has been done by several groups in both the public and private sectors.

Phosphate rock (defined as rock which contains greater than 13.8 percent P_2O_5 by weight) occurs within the Lisburne Group rocks (Mississippian age) along the northern front and the southern foothills regions of the Brooks Range (Patton and Matzko, 1959). The localities in NPRA (within Region 2 on figure 1) were described by Patton and Matzko as "thin beds of phosphate rock or phosphatic (greater than 5.0, but less than 13.8 percent P_2O_5) mudstone, with grades of up to 24.8 percent P_2O_5." Elsewhere in northern Alaska, the Shublik Formation

of Triassic age also contains concentrations of phosphatic materials. High-grade phosphate occurrences in Shublik rocks have not been identified in NPRA, but there has been no systematic exploration for phosphate rock in either the Lisburne or Shublik rock units in NPRA.

Nearly all of the phosphate rock reported in the NPRA (Patton and Matzko, 1959; Tourtelot and Tailleur, 1965) is of low or medium grade, although samples from the Shublik Formation in the eastern Brooks Range contain as much as 35.8 percent P_2O_5. Small amounts of uranium (up to 0.008 percent uranium, reported by Patton and Matzko, 1959), are associated with the northern Alaska phosphate rock samples. The uranium concentrations may be sufficient to represent a potentially valuable by-product.

Other elements of potential interest found in some of the phosphatic rocks include nickel, chromium, vanadium, copper, yttrium, molybdenum, cadmium, and lead. Recovery of these would increase the value and enhance the development of phosphate resources which might be delineated. Data on the deposits are insufficient to make estimates of phosphate resources, or reserves calculations. Further exploration is warranted, particularly within those appropriate Lisburne and Shublik horizons, for phosphate and associated by-product elements.

Preliminary examinations of selected oil shales from northern Alaska have been made by both the public and private sectors. In addition to the interest in oil shales for their hydrocarbon content, attention has been devoted to the possibilities of extracting various associated metals.

Oil shales occur in Triassic to Middle Cretaceous rocks in the southern foothills of NPRA. Descriptions and analytical results are given in Tailleur (1964) and Tourtelot and Tailleur (1965, 1967). The oil shale horizons lie in a structurally complex geologic setting. The extent and thicknesses of oil shales and their host rocks is unclear, and appropriate geologic mapping is needed.

In addition to the high content of organic matter, the oil shale samples contained anomalously high concentrations of the following metals: copper (up to 0.048 percent), cobalt (to 0.024 percent), molybdenum (to 0.044percent), nickel (to 0.096 percent), vanadium (to 0.31 percent), barium (to 6.27 percent BaO), and zinc (to 0.7 percent).

Other elements with noteworthy levels of concentration were silver, gold, mercury and arsenic. These associated heavy metals may be recoverable by-products if the oil shales are developed. An

evaluation of the oil shales requires further information on their extent, as well as further sampling and analysis of the metal content and a determination of the manner(s) of the metal incorporation.

4. Perspectives

Compelling arguments can be made for the potential significance of zinc, lead, and silver occurrences such as those found at Drenchwater Creek, Story Creek, and Kivliktort Mountain. Economic mining feasibility has been established for the Red Dog deposit. The geologic setting at that deposit is similar to those of the known mineral occurrences to the north and east.

The Red Dog deposit, and surrounding area, have been discussed by numerous authors since its announced discovery in 1975 by the U.S. Bureau of Mines. The most relevant of these have been cited above, and/or are listed in the references of the present paper.

As summarized by Lange et al. (1985):

> Major stratiform sphalerite- galena-barite deposits occur in the Red Dog Creek and Drenchwater Creek areas in the northwestern Brooks Range, Alaska... Deposits in the two areas are similar and consist largely of sphalerite, galena, pyrite, and barite. They are hosted in an unnamed Mississippian and Pennsylvanian unit comprising chert, shale, quartz exhalite, tuff, tuffaceous sandstone, keratophyre, and andesite. These rocks are part of the Kagvik structural sequence... that also includes chert and shale of Permian and Triassic age, and graywacke and mudstone of the Cretaceous Okpikruak Formation. The Drenchwater Creek area occurs within the center of the east-west-striking belt of the Kagvik sequence; the Red Dog Creek area is near the western edge of the belt... Parts of the Kagvik sequence between the two areas and beyond them have significant potential for undiscovered stratiform zinc-lead-barium deposits... and constitute a major new mineral belt in North America.
>
> Exploration, discovery, and study of the stratiform deposits in the Red Dog Creek and Drenchwater Creek areas arose in part from intense interest in such deposits in other regions of the world. These types of deposits generally occur in carbonate and siliciclastic rocks... Deposits of this type are thought to be the product of

exhalation of hydrothermal fluids. These include the extensive shale-hosted Howard Pass deposits that contain several hundred million metric tons of Zn-Pb ore, the Macmillan Pass Camp, and the Anvil Camp all within the Selwyn basin...

This paper discusses the geologic setting, structure, petrology, geochemistry and origin of the host rocks and stratiform sphalerite-galena-barite deposits of the Red Dog Creek and Drenchwater Creek areas. The paper also shows the extremely similar geologic setting, petrology, geochemistry, and origin of the two deposits.

Perspectives on the Red Dog deposit, in relation to present concerns in the Western Arctic study area, were summarized recently by Mowatt et al. (1990), as follows:

The Red Dog mineral deposit is located in northwestern Alaska, about 90miles north of the village of Kotzebue. Red Dog Creek flows across it; the creek bed, banks, and surrounding rocks are intensely-stained in red-orange colors, due to weathering of mineralized bedrock, principally carbonaceous shale-chert of Mississippian-Pennsylvanian age. Mineralization consists of fine-grained to massive, variously stratiform-lens-vein-breccia-filling sulfides and barite. Ore reserves approximate at least 85 million tons, with grades of 17.1 percent zinc, 5.0 percent lead, and 2.5 ounces silver per ton.

Red Dog is the second largest deposit of zinc ever discovered, exceeded only by the original Broken Hill, Australia, deposit. Concentrate shipments are to begin in 1990. Red Dog will then be the largest base metal mine in the world, estimated to contain at least 15 million tons of zinc, hence will be a major long-term source of this important metal for global society. Significant economic benefits will accrue to involved private sector organizations, as well as to various local, state, and national economies. There are also indications of additional mineralization of similar character in the vicinity, hence additional resources may be developed as well.

In this perspective, the history of events which led to recognition, delineation, and development affords an

important example for similar future endeavors. The roles played by government–federal and state– private, and academic sectors merit accurate recapitulation, in context of present and future concerns and policies regarding continuing need for mineral resources to meet the requirements of society...

Despite occasional problems attendant to interfacing and defining/clarifying roles, overall results indicate relatively effective meshing of government organizations, private and academic sectors, during the lengthy course from discovery to production of an important mineral deposit. As debate continues as to future sources -- availabilities of mineral resources, development-consumption, other resources/land-use values, environmental considerations, government-private sector roles, etc., the Red Dog example should provide useful insights.

Adjacent to the Red Dog proper, similar mineralization has been discovered ("Lik, Kik"). Forrest and Sawkins, 1987, summarize the relationships and implications as follows:

The Lik massive sulfide body is one of several recently discovered sediment-hosted zinc-lead-silver deposits in the western Brooks Range. These late Paleozoic deposits form a belt, which extends eastward from the Lik and Red Dog deposits for over 250 km, that includes mineralization at Ginny Creek and Drenchwater Creek... Lik contains 25million tons grading 8.8 percent Zn, 3.0 percent Pb, 38 g/ton Ag, and the nearby Red Dog sulfide body contains 85 million tons grading 17.1 percent Zn, 5.0 percent Pb, and 91 g/ton Ag... The aggregate tonnage of these new deposits makes this one of the largest zinc-lead-silver districts in North America.

Field mapping, core logging, and petrographic studies of Lik presented herein, plus preliminary data from Red Dog and the other mineralized areas... indicate that all of the sulfide bodies in the belt are sediment-hosted, submarine exhalative, zinc-lead-silver deposits. The term sedex has been applied to this type of mineralization... Although sedex deposits exhibit considerable variation, they commonly contain the following features: (1) synsedimentary zinc-lead-silver mineralization that formed during the expulsion of

> metalliferous fluids into a submarine environment, (2) sulfide deposition in a second-or third-order basin, which developed in a tensional or pre-rift setting, (3) volcanic activity that may be associated with the deposits in time but not necessarily in space, and (4) sulfides accumulated on or near the sea floor that may be early epigenetic as in the case of the H.Y.C. deposit at McArthur, Australia... and or syngenetic...

An indication as to the viability of these deposits was the fact that major mining companies working since 1976 in the Red Dog Creek/Wulik River areas of northwestern Alaska had spent at least $6,000,000 through 1978 on exploration in order to define potential ore bodies. Many years (1975-1982) of effort were required before the nature and extent of the near-surface mineralization was elucidated in that one relatively small area. Similar orders of magnitude of expenditures of time and money are required to achieve similar understanding of the mineralization of analogous small parts of the study area.

Another intriguing potential metallic mineral resource, the platinum- group elements, remains less well-defined, in and adjacent to the study area.

Economic extraction of mineral resources is closely tied to accessibility and transportation infrastructures. Continued access throughout the study area will be essential to obtain information required to evaluate the mineral resource base and to permit development of any potential mine site and related facilities. Transportation corridors either to the sea or connecting with the contiguous transportation network in Alaska are essential (cf. Heiner and Wolff, 1969; Clark, 1973; Rao and Wolff, 1975) in making the mineral resources available to the nation.

The United States is heavily dependent on imports of many of the minerals and metals discussed in this paper. Some of these commodities are classed as of "critical/strategic" importance to the U.S.A. National needs will require adequate continuing supplies of various mineral resource commodities. Many years of lead time are required to identify and develop sources of needed materials (cf. The Red Dog example, Mowatt et al., 1990).

Only very limited assessment of the significance of the potential resources of the study area to the local area, state, or nation is possible with the present data base. The available mineral resource data for the study area indicate the strong desirability of planning in order to facilitate commodity exploration, development, and extraction.

5. Current Land Status and Management

All of the NPRA, and adjacent public lands in the study area, are presently withdrawn from mineral entry under the federal mining laws (Cape Krusenstern National Monument, Noatak National Preserve, Gates of the Arctic National Park) or are either in the process of, or have been, transferred from federal to state of Alaska or private entities, under the aegis of ANCSA-ANILCA.

Thus, with the exception of valid mining claims or mineral patents within the study area, there are no known exploration, development or production operations planned within the study area, on federally managed lands, at the present time. Proposed activities in this context were presented under Section IV, Capability Analysis/Management Opportunities, of the BLM Western Arctic Resource Management Plan (presently in draft form).

Current management precludes further exploration, development and production activities related to mineral resources on federal lands within the study area.

There are decided management opportunities within the study area with regard to mineral resources. A significant portion of the study area contains what has been termed a "world-class mineral belt" by knowledgeable technical personnel.

The outstandingly successful example of the history of the discovery, delineation and development of the Red Dog deposit, the second largest zinc deposit ever found, to date, worldwide (cf. Mowatt et al., 1990) is most appropriate in the broader context of the area. Known geologic relationships and mineral occurrences strongly indicate the distinct likelihood of analogous deposits elsewhere within Region 2 of the study area.

Extensive zones having mineral resource potential can be identified in the study area, but as yet there are no additional proven reserves.

Although, as the senior author can attest, the Red Dog deposit would indeed have been difficult for any competent minerals exploration geologist to overlook, from the air or on the ground, still its recognition and delineation came about only as the product of a lengthy period of time, and the convergence of a number of favorable circumstances.

As discussed by Mowatt et al., 1990:

> Subsequent to the enaction of the Alaska Native Claims Settlement Act (ANCSA), the U.S. Bureau of Mines (USBM) had been directed by the U.S. Congress to carry out investigations of the nature and resource potential of known or reported occurrences of mineralization across broad regions of federal lands in Alaska which had been withdrawn from mineral claim-staking by ANCSA (the so-called "d-2 lands"). As part of these investigations, in 1975 the USBM initiated a program of systematic field and laboratory work to characterize and evaluate known mineral resources or geochemical anomalies across a major portion of the western Brooks Range and adjacent areas. This included the Wulik River and Red Dog Creek areas. The work was done principally via contract to private sector entities with relevant experience and expertise, directed and supplemented by USBM personnel.
>
> It should be noted that the funds made available to the USBM for this work amounted to approximately 4 percent of the level considered to be minimally adequate, on a per-acre basis, for technically substantive mineral resource exploration (exclusive of subsurface sampling) by experienced and competent private sector organizations. In fact, the level of funding resulted in coverage of these withdrawn Alaskan lands at a level of approximately 20 percent of that considered by the United Nations to be the minimum necessary to categorize lands as other than 'essentially unexplored.'
>
> Additionally, the USBM program was restricted to surface sampling only, so that 'visual impacts' to these withdrawn lands would not result...

Such significant results as the discovery of a Red Dog-class deposit, for such a relatively minimal effort in terms of time and funding, are quite unusual. A much more complete and substantially funded program is needed to thoroughly assess the mineral resources potential of the study area.

In order to substantively elucidate such other mineral resources as may occur within the study area, a more precise and complete data base is required. At this time, short of permitting normal mineral entry and/or leasing activities, an alternative is a program–presumably by, or

under the direction of the federal government–of exploration which would provide a sound basis for land use planning and resource management.

Such a program should consist of:

1. Systematic field mapping of exposed geologic materials (at 1:250,000 and better), supplemented by regional geochemical and geophysical work to provide a comprehensive knowledge of the geologic framework.

2. Field mapping and sampling on appropriate larger scales, supported by studies of the petrology, mineralogy, geochronology, paleontology, geochemistry, geophysics, and economic geology, to provide information on critical areas or relationships, as well as to characterize the mineralized rocks and potential resources.

3. Mineral resource definition, based on 1 and 2, to include detailed mapping, sampling (including drilling), laboratory and site-specific studies.

4. Planning for resource development, based on accumulated knowledge that leads to elucidation of mineral occurrences, including reserve delineation, resource projection, transportation, environmental and reclamation considerations.

Selected belts within identified geochemical zones in Region 2 (*Figure 1*) can be identified for detailed base metal exploration. For example, detailed sampling could be undertaken for near-surface lead-zinc-silver-cadmium mineralization within the regional geochemical trends along which base and precious metal occurrences have been found and which suggest a high likelihood of additional similar mineralization. Table 1 gives locations and sampled surface materials for some possible target areas identified by field studies of 1977 and 1978 (DOI, 1978).

Detailed geologic mapping along these trends in the three mineralized geologic zones in Region 2 is required to define the nature and controls of the mineralization. Studies in the easternmost zone could be initiated along the Story Creek - Koiyaktot Mountain trend, and in areas containing identified geochemical anomalies associated with Devonian rocks.

Another zone, of particular interest for prospecting and sampling, would be the Drenchwater Creek area and geochemical anomalies associated with Mississippian rocks. Uninvestigated anomalies,

similar to those associated with mineralization, have been identified in the geochemical trends and could be explored initially, as well.

Detailed, site-specific work could be undertaken in the areas of identified significant mineralization such as the Drenchwater Creek, Story Creek, and Kivliktort - Koiyaktot Mountain areas. In addition to the geological and geochemical work, surface geophysical surveys and core drilling of appropriate targets would define the extent of mineralization. Systematic work of this type is the only way to define available near-surface resources and their distribution.

Such a step-wise exploration program could be applied to each commodity to define the character and extent as well as the significance (local, statewide, or national) of the mineral(s). A reasonable timeframe for completion of an intensive "first-pass" exploration program might be on the order of 5 years; detailed studies would be scheduled on an as-yet-to-be-devised priority scheme dependent on the basic information and societal requirements.

Thus, as discussed in DOI, 1978, "Management options could include: (1)opening NPRA to mineral entry under all existing mining and regulatory legislation; (2) government management of exploration to be carried out by private contractors, with resources disposition deferred pending acquisition of data; and (3) government exploration with resource disposition deferred as above."

Mineral exploration, evaluation and development might well be done most efficiently and effectively under a management scheme utilizing presently existing laws regarding mineral entry/leasing of various locatable, leasable, and salable commodities. This reduces government involvement and enables the private sector to assume its traditional role in a geographic area from which it has been excluded. Industry exploration (option 1, above) historically has proven to be the most effective and least expensive method for the nation to identify mineral resources and reserves, although options 2 and 3, above, were of paramount significance during the recognition of Red Dog and the similar deposits in the region (Jansons, 1982; Mowatt et al., 1990).

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Table 1.
Locations and surface materials of possible exploration targets identified by Bureau of Mines, 1977-78 (from DOI, 1978).

Site	Surface Materials, Remarks
Upper Kagvik Creek	Pyritiferous cherts, black shales
Ilingnorak Creek	Iron oxides in greywackes
Elbow Creek	Pyritiferous cherts and tuffs
Chertchip Creek	Black shales, pyritiferous chert
Rampart/Recon/ Jubilee Creeks	Pyritiferous chert
Drenchwater Creek	Volcanogenic base-metal sulfides
Upper False Wager Creek	Pyritiferous chert
Kiligwa River	Pyritiferous chert
Boundary area	Iron oxides in creek bed
Cutaway Creek	Pyritiferous chert, petroliferous chert
Lisburne Ridge	Phosphatic shale reported
Mount Bupto	Fluorite
Safari Creek I	Barite nodules, shales
Safari Creek II	Pyritiferous carbonates, black shales
Siniktanneyak	Mineralized rock, zinc and lead;
Mountain	mafic-ultramafic rocks, PGE
Spike Creek	Pyritiferous chert
Rolling Pin Creek	Pyritiferous chert
Story Creek	Massive high-grade zinc mineralization
Kivliktort Mountain (W)	Devonian conglomerates, shales, quartzites, pyritiferous sandstones
Kivliktort Mountain (E)	Zinc in Devonian sedimentary rocks

Site	Surface Materials, Remarks
Koiyaktot Mountain	Devonian sandstones, conglomerates; minor but widespread galena, sphalerite; anomalous values from stream sediment analyses
Isikut Mountain	Devonian quartzites, sandstones; low-level zinc geochemical values, minor zinc oxides and galena in upper reaches of drainage
Ipnavik River	Devonian chert pebble conglomerates, sandstones and shales; anomalous lead and moderately anomalous zinc in stream sediments Memorial Creek Pyritiferous sandstones, gossans
Safari Creek (upper)	Red and green shales, carbonaceous shales, anomalous zinc and lead in stream sediments
Twistem Creek	Black shales; high zinc values, high radiometric counts
Swayback Creek	Stream sediment samples only, anomalous lead and zinc in original sediment sample
Mount Bupto	Kerogenous shale; flourite in carbonate
Plunge Creek	Cretaceous sedimentary rocks; stream sediment samples; anomalous lead value; within much larger Driftwood anomaly
Spike Creek	Carbonates, shales, pyritiferous cherts, anomalous zinc, lead copper, silver, barium geochemical values
Anisak River	Limestones, cherts, diabase, pyritiferous cherts; high lead and zinc values; 5 tributaries investigated
Trail Creek	Pyritiferous carbonates and chert float, anomalous zinc
Inaccessible Ridge	Carbonate sequence; highly anomalous copper stream sediment geochemistry

Site	Surface Materials, Remarks
Ignisirok area	Black shales, pyritiferous cherts; siliceous mudstones; high zinc values; notable gossan
Sphinx Mountain	Shales, carbonates, cherts; highly anomalous zinc and copper from stream sediment analyses
Kagvik Creek	Carbonates, shales, cherts; high zinc in stream sediment samples; 7 creeks sampled; barite float
Sharp Peak	Sandstone, conglomerates, mudstones; high zinc, barium, molybdenum
Mechanic Creek	Black shales, carbonates, gossans in drainage; high zinc geochemistry
Nuka	Pyritiferous cherts, gossan cherts
Nuka Ridge	Sandstones, shales; some with "oil shale" strong "asphaltic" odor
Signayoak - Picnic Creek	Sedimentary rocks (Cretaceous-Mississippian), clastics, anomalous high lead in stream sediment samples
Nigu Bluff	Pyritiferous diabase

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